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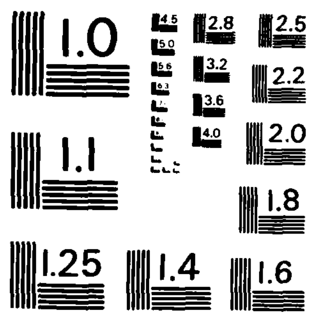

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POLARIZATION STUDIES IN ELECTRON CYCLOTRON HEATING EXPERIMENTS ON THE VERSATOR II TOKAMAK

JAYCOR Report J206-82-011/6202

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Preliminary results of the ECH experiment using the MIT Versator II with polarized microwave radiation were obtained. Decreases in both loop voltage and line average plasma density were measured as a function of power and toroidal angle of microwave beam injection. Thompson scattering measurements indicate an increase in the central electron temperature. These investigations showed a distinct asymmetry behavior for both polarizations.

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I. INTRODUCTION

It has been shown that plasma heating by microwaves at the electron cyclotron frequency is effective in a variety of confinement devices. While extensive research has been conducted using Electron Cyclotron Heating (ECH) in cold toroidally confined plasmas, only recently has it become possible to perform such an experiment on the hot, well confined plasmas in a tokamak. This advance has been made possible by the development of high power, short wavelength gyrotron oscillators.

The absorption mechanisms are distinctly different for cold and hot plasmas. The theoretical effects of polarization were predicted but their experimental verification had not been achieved prior to this effort, which investigated the absorption of polarized microwave radiation in the MIT Versator II tokamak. These experiments concentrated on the measurement of single pass and multiple pass absorption of both the ordinary and the extraordinary waves. Comparisons were made with theoretical estimates of absorption. Investigations of the combined effects of electron cyclotron and lower hybrid resonanace heating, and preionization effects on runaway electron generation were also accomplished.

The experimental investigations were conducted at the Massachusetts Institute of Technology (MIT) Laboratory in Cambridge, Massachusetts, using their Versator II tokamak and an NRL microwave source. The microwave source was a 35 GHz gyrotron with 20-150 kW output power, pulse length $t \leq 20$ ms, and a circular output mode TE_{01}. The characteristics of the Versator II tokamak are given in Table 1. Several features of this device are especially suited for these experiments. First the toroidal magnetic field allows the electron cyclotron resonance to be located at any desired major radius inside (or outside) the tokamak. Secondly, the tokamak operates well at a magnetic field of 6.25 kG, which would enable heating at the second harmonic of the cyclotron frequency. It is possible with the Versator II tokamak to locate the fundamental ($\omega = \Omega_c$) and second harmonic ($\omega = 2\Omega_c$) resonances outside of the plasma to demonstrate that plasma heating is

TABLE 1

VERSATOR II PARAMETERS

MAJOR RADIUS	$R_o = 40.5$ cm
MINOR RADIUS	$\alpha = 13$ cm
ELECTRON TEMPERATURE	$T \cong 350$ eV
ION TEMPERATURE	$T \cong 80$ eV
ELECTRON DENSITY	$n_e \cong 1\text{-}3 \times 10^{13}$ cm^{-3}
TOROIDAL MAGNETIC FIELD (ON AXIS)	$B_T = 6 - 15$ kG
PLASMA CURRENT	$I_p = 30 - 40$ kA
PULSE LENGTH	$\tau_p = 25 - 30$ ms
ENERGY CONFINEMENT TIME	$\tau_E \leq 1$ ms
OHMIC HEATING POWER	$P_\Omega < 100$ kW

due to electron cyclotron absorption.

Previous attempts to polarize high power (~100 kW) microwaves for ECH were limited by microwave breakdown in commercially available ($TE^0_{01} \rightarrow TE^0_{10}$) mode transducers. The experiments employed polarizing antennas which operate with overmode waveguides. Two types of antennas investigated were:

1) the Wengenroth, or step plate reflector, and
2) the "Vlasov" antenna

Both of these antennas convert TE^0_{0n} waveguide modes to crudely polarized TEM waves.

The experimental configuration is shown in Figure 1. In order to avoid cutoff, the extraordinary wave was injected from the high magnetic field side of the device. The ordinary wave was launched from the low field side of the device. The single pass absorption of the extraordinary wave was expected to be higher than for the ordinary wave.

An experiment performed for the first time in a tokamak was the combination of electron cyclotron heating ($\lesssim$100 kW) and lower hybrid resonance heating (~90 kW). This experiment was of particular importance because the total wave heating power is about twice the initial ohmic heating power. The interaction of the two heating mechanisms was studied experimentally.

Another set of experiments, considered for the Versator II, concerned the effects of ECH preionization on tokamak discharges. It was possible to conduct detailed measurements on preionization with Versator II because of the capability of inserting probes into the tokamak plasma. Another issue to be investigated was that the Versator II typically generates runaway electrons which were expected to be reduced by preionization.

The Versator II tokamak operates at a lower optical depth than the ISX-B, on which the previous ECH experiments were conducted. It was expected that the incident microwave power would not undergo 100 percent absorption in a single pass through the Versator II plasma. Another difference between the two tokamaks is that the electron energy confinement time in Versator II is 1/10 of the value in ISX-B. This means that the 10 ms microwave pulse will effectively be CW for the plasma. These considerations led to lower ECH efficiency in Versator II than in the previous experiments.

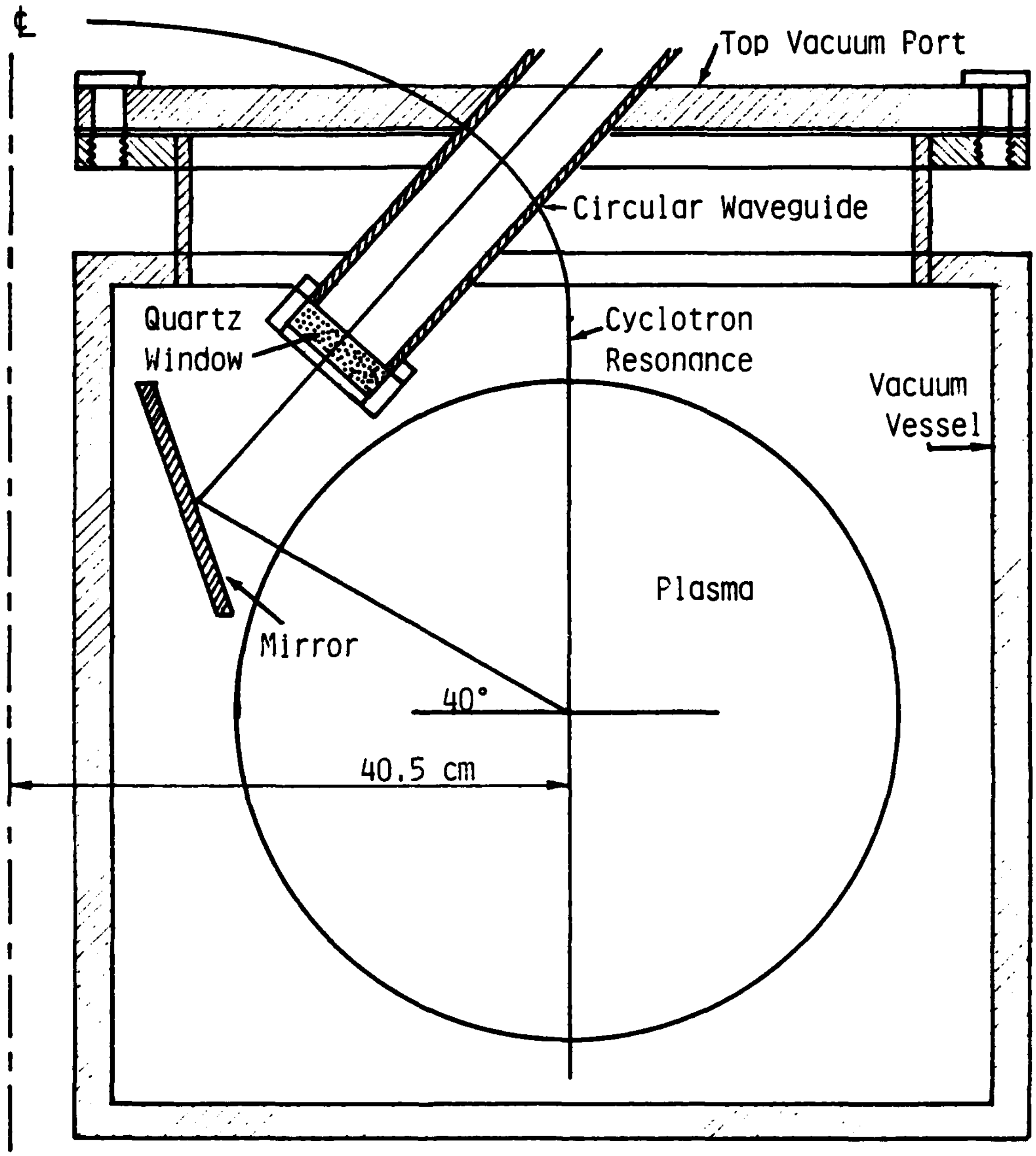


Figure 1: Experimental Configuration on Versator II Tokamak

II. THE EXPERIMENTAL PROGRAM

The experimental program, conducted at MIT Laboratory, using the Versator II tokamak, relied on the laboratory staff graduate students and technicians for its operation, maintenance and repair. There were considerable delays in the program schedule due to maintenance and repair of the tokamak. The following paragraphs discuss the program progress by quarters during the contract period of performance.

The first quarter's major effort for the Electron Cyclotron Heating (ECH) experiment was in the design, construction and testing of the RF transmission system. The proposed design called for propagation of the RF in the TE_{01}^{0} mode from the gyrotron into the tokamak with a mode transducing mirror within the tokamak to polarize the radiation for either the ordinary or extraordinary mode experiments. Tests of this design showed it to be unsuitable for the planned studies of the dependence of ECH efficiency on the launch angle of the RF into the plasma. The design shown in Figure 2 was employed instead. The polarization of the RF occurs by first converting the TE_{01}^{0} to $TE_{10}^{\square}$ and then to TE_{11}^{0}, which has the required polarization. To suppress electrical breakdown in the transmission system, the waveguide can be pressurized with SF_6, or near the tokamak, N_2. In the event arcing did occur, provisions were made for rapidly purging the SF_6 breakdown products from the transmission system. Low-power tests indicated a transmission loss of 1.5 - 1.8 db, so that 100 kW or more of polarized RF power should be available for ECH, assuming a gyrotron output of 150 kW. Initial high-power tests evidenced no breakdown problems in the waveguide. With successful completion of further high-power tests, which were delayed by a thermal short in the gyrotron magnet, ECH experiments began with the extraordinary mode incident from the high field side of the tokamak.

To provide a frame work for interperting observations of temperature and density profile modifications by ECH, a computer code to model the transport processes in the tokamak was developed. The code is an adoption of that developed by Dr. R. Englade of MIT. The code was orginally developed for investigating the lower hybrid heating on the

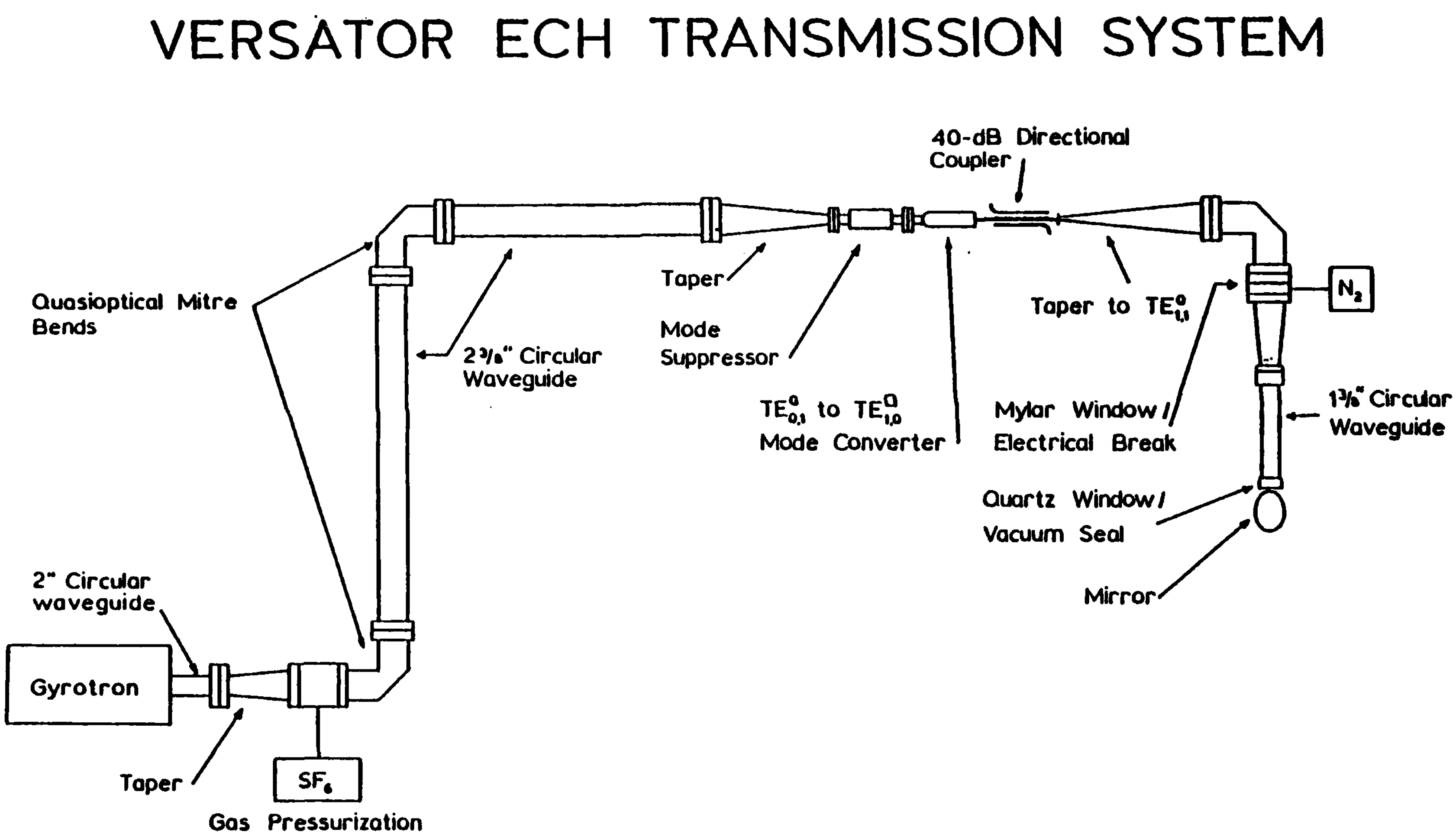


Figure 2: Schematic of Versator ECH Transmission System

Versator II tokamak.

During the second quarter, the installation and testing of the NRL 35 GHz, 150 kW TE_{01} (circular) gyrotron and transmission system to inject the microwave into the Versator II was completed. Initial plasma heating experiments were successfully performed.

These initial experiments indicated that the influence of microwave pulses on the plasma was strongly dependent on its initial state. Without ECH, the discharge was characterized by a nearly constant density, $\overline{n}_e \cong 1.2 \times 10^{13}$ cm^{-3}, lasting about 15 ms with $I_p \cong 33$ kA and loop voltage $V_L \cong 1.8$ V. The gyrotron was pulsed for 3 ms at the time of maximum current with the transmission system adjusted for the extraordinary mode. No increase in impurity line radiation was observed. Heating the discharge from a different set of initial conditions will be discussed later.

Two effects of the ECH pulse were immediately apparent. As seen in Figure 3, there was a decrease in the loop voltage as it returned to its normal level after the pulse, while the density showed a marked increase compared to its value without an ECH pulse. The IN/OUT monitor showed that the plasma was well centered before the ECH pulse, moving toward the outside during the pulse only after the loop voltage and density had stabilized at their lowered values.

The dependence of $\Delta V_L/V_L$ and $\Delta \overline{n}_e/\overline{n}_e$ on microwave power, P_{ECH}, and injection angle, θ, is shown in Figures 4 and 5, respectively. Both effects are larger and still increasing at high power at the intermediate angles of 15° and 30°, while they are smaller and show signs of saturation at 0° and 40°.

Preliminary Thompson scattering measurements of the central electron temperature were made for the case of $\theta = 40°$. T_{e0} rose from 226 ± 58 eV to 350 ± 89 eV for $P_{ECH} = 62$ kW, associated with an 11 percent decrease in V_L.

By decreasing the toroidal magnetic field, the position of the cyclotron resonance was moved toward the inside of the torus by about 4 cm. The loop voltage decrease was not significantly altered; the density decrease did, however, disappear.

Another set of initial conditions for a discharge studied were $\overline{n}_e \cong 6.6 \times 10^{12}$ cm^{-3}, $I_p = 20$ kA; $V_L = 1.0$ V at the time of the microwave

TYPICAL V_L & $\bar{n}_e$ DURING ECH

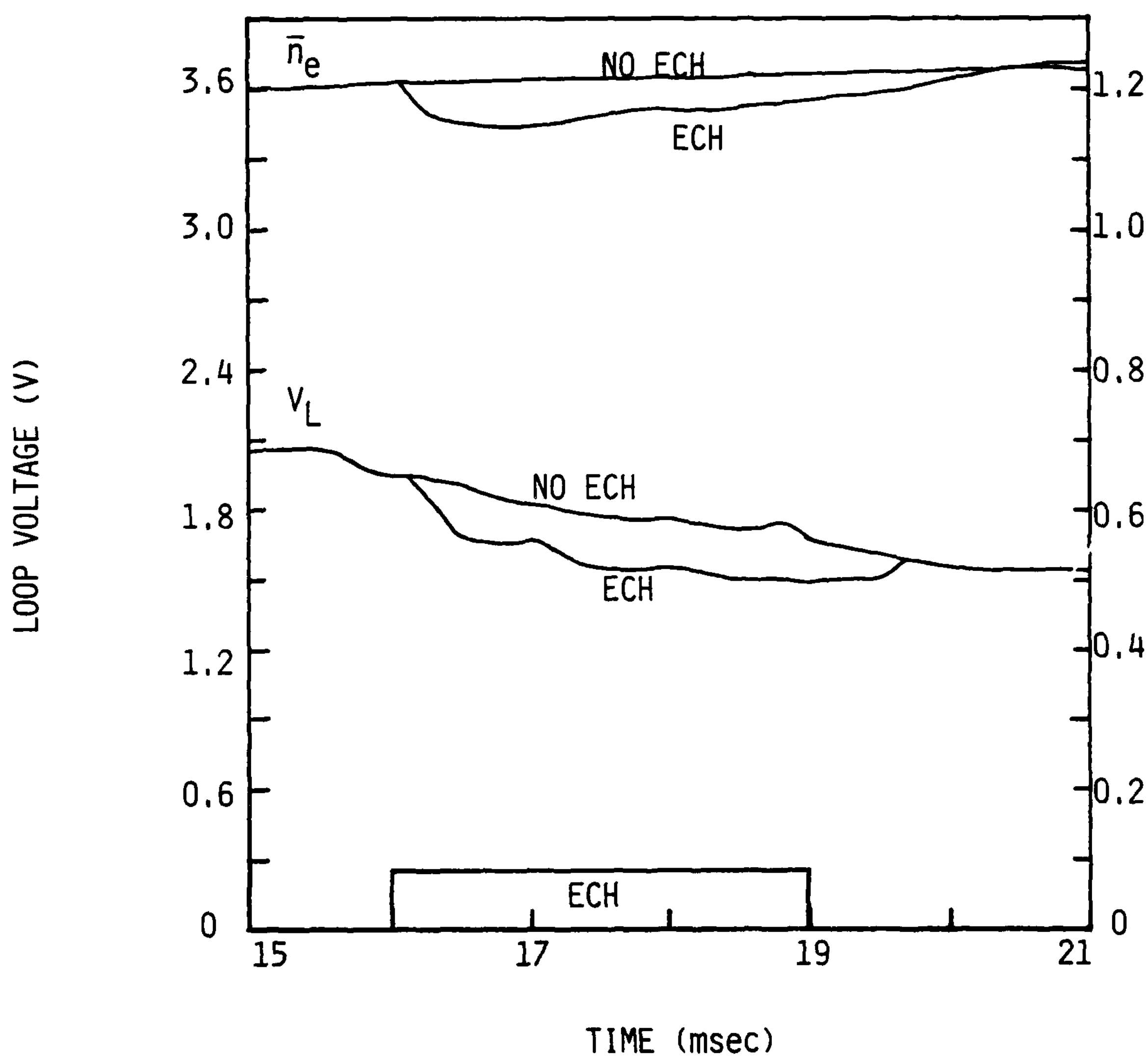


Figure 3.

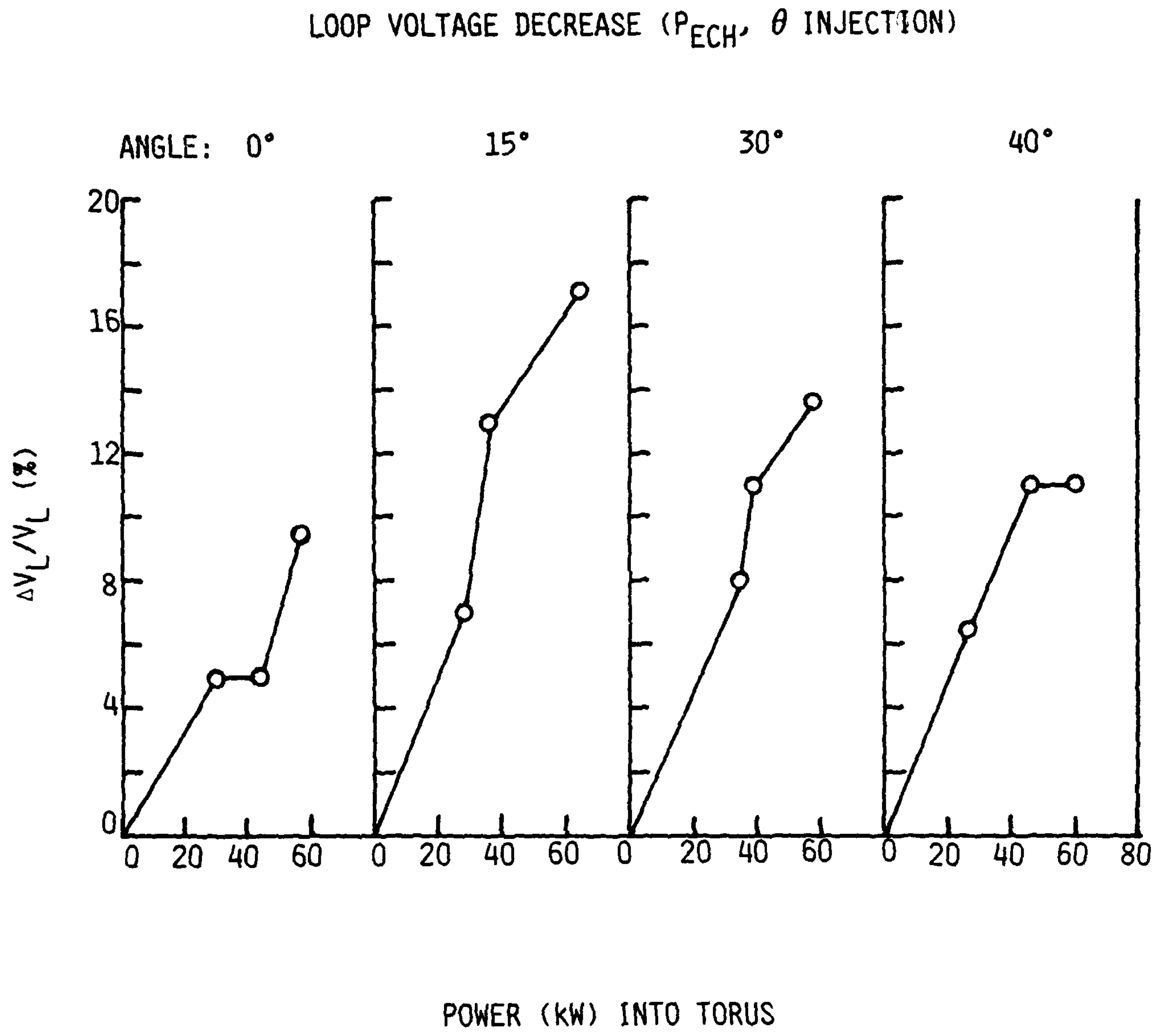
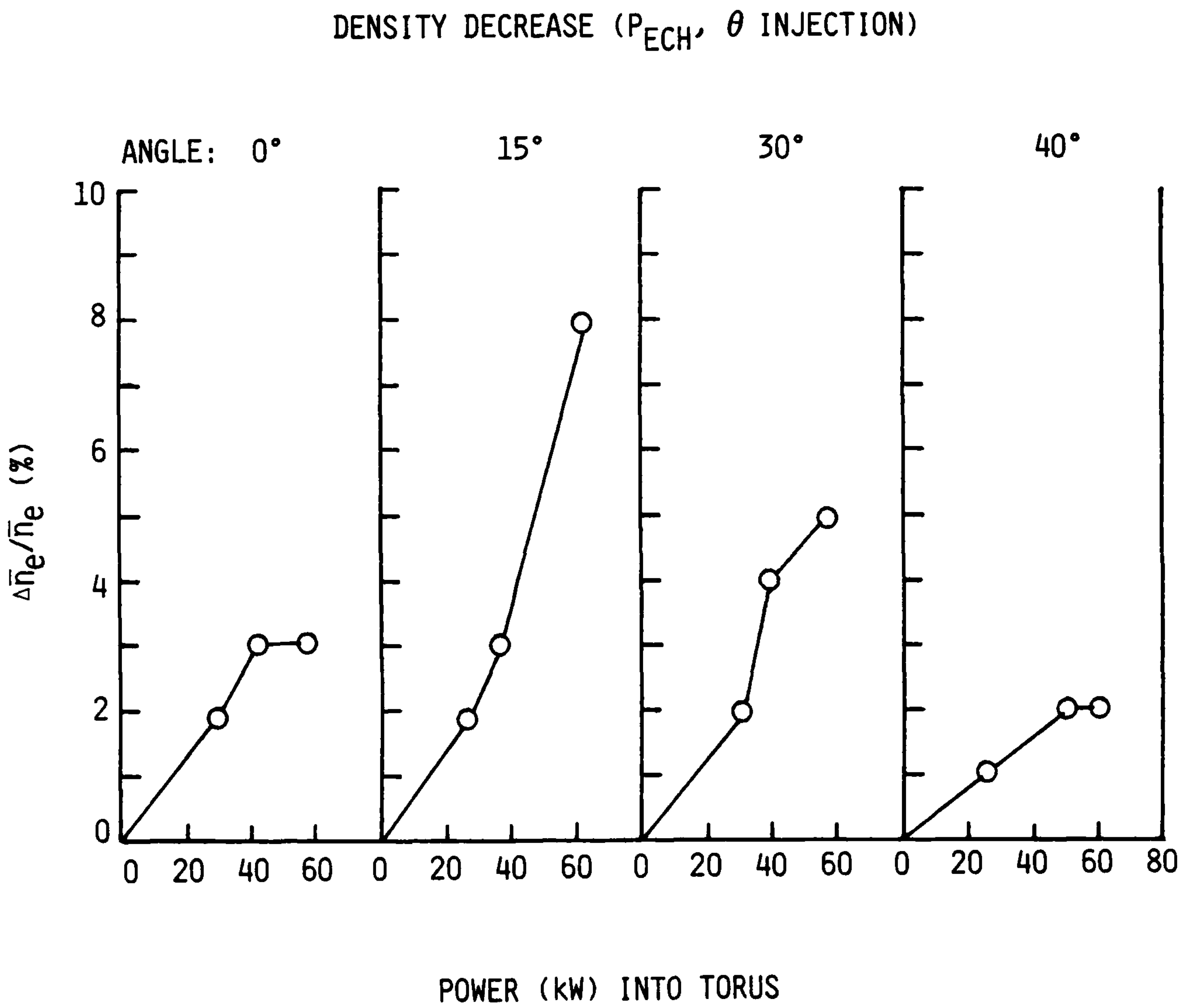

LOOP VOLTAGE DECREASE (P_{ECH}, θ INJECTION)
ANGLE: 0°
15°
30°
40°
$\Delta V_L/V_L$ (%)
20
16
12
8
4
0
0
20
40
60
80
POWER (kW) INTO TORUS

Figure 4.



DENSITY DECREASE (P_{ECH}, θ INJECTION)
ANGLE: 0°
15°
30°
40°
$\Delta\bar{n}_e/\bar{n}_e$ (%)
0
2
4
6
8
10
0 20 40 60
0 20 40 60
0 20 40 60
0 20 40 60 80
POWER (kW) INTO TORUS

Figure 5.

pulse. Neither the current nor the density were constant for an extended period of time. Perpendicular injection of 60 kW of extraordinary mode radiation produced a 50 percent decrease in V_L and a 30 percent decrease in $\bar{n}_e$. The plasma moved toward the inside of the torus with a substantial increase in the impurity line radiation. The loop voltage became very noisy after the pulse, with positive voltage spikes of 3-4 V, lasting a few hundred microseconds. Thompson scattering showed T_{e0} to increase from 179 ± 21 eV to 275 ± 45 eV.

Many interesting points were observed which indicate key problems for further study. The first discharge described showed only a small (≅5 percent) density decrease, while the second discharge produced a much larger, (≅30 percent) decrease. Density decreases as large as 70 percent have been observed on occasion. What causes these decreases, and what determines their saturated values, is as yet unknown. Their relation to loop voltage decreases is also unclear, but based on observations with varying the toroidal magnetic field, the two may be manifestations of different physical processes.

The single-pass absorption coefficient for extraordinary mode heating should be increasing with angle, θ, with a corresponding decrease in loop voltage throughout the range studied[1,2]. The observed decrease in loop voltage, an indication of heating, does not follow the expected angular dependence. It is necessary to understand the causes of the angular dependence so that the optimal injection angle for ECH can be found.

These results were presented at the Fourth Topical Conference on RF Plasma Heating. The paper is included as Appendix A. A problem with the experiments was that the Thompson scattering diagnostic was not operating reliably. The indication of plasma heating was inferred from the decrease in loop voltage. The problem was later corrected by the Versator II staff.

Progress in the third quarter was severely limited. Expectations were to continue the measurements of loop voltage and

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[1] O.C. Eldridge, et al., ORNL/TM-6052, Oak Ridge National Labaratory (1977).
[2] E. Ott, B. Hui and K.R. Chu, Phys. Fluids 23, 1031 (1980).

density decreases caused by ECH in the extraordinary mode as a function of microwave power and injection angle. These measurements were to be complemented with a comprehensive set of Thompson scattering measurements of the central temperature with microwave injection in both the extraordinary and ordinary modes. Due to tokamak operational failures, the anticipated experiments were not performed, however, several interesting observations were made during this period.

There appears to be a very narrow range of plasma density within which ECH is effective on the Versator. For a line-average density below $\cong 4.0 \times 10^{12}$ cm^{-3}, Versator II produces a run-away discharge which does not heat well; above $\cong 1.6 \times 10^{13}$ cm^{-3} the discharge again does not seem to heat. (This latter point is similar to results from JFT-2.) There is also a distinct asymmetry of heating efficiency with injection angle; co-injection, with respect to the toroidal current, is more efficient than counter-injection. This is to be expected for ECH current-drive, but the single-pass absorption coefficient is predicted to be too low for this process to occur. Although a complete radial profile has not been taken, strong heating has been observed at the minor radius of 7.6 cm (the minor radius of Versator II is 13 cm); the temperature increased from 107 to 214 eV, while the central temperatures rose from 336 to 510 eV.

In a related experiment, preliminary indication of a 3-wave parametric interaction has been observed. Emission from the plasma at 350 MHz below the gyrotron frequency has been observed coincident with a 350 MHz oscillation of the plasma density behind the limiters. Determination of the plasma modes present will indicate the impact this interaction will have on heating efficiency.

Combined ECH, lower-hybrid experiments were started the third quarter. The initial indications were that ECH can suppress instabilities triggered by lower-hybrid current-drive and increase the total current. Whether the additional current is truly "driven", or a result of having lowered the plasma resistivity by heating it, has not, as yet, been determined.

Progress during the fourth quarter was again severely limited due to breakdown of the Versator II tokamak and its essential diagnostics. Failure of the ohmic heating coil cost the program 40

percent of its allotted machine time. The Thompson scattering system on which we rely for basic temperature measurements, has suffered a variety of problems, ranging from mechanical failure of a hydraulic jack to rapid drift of photomultiplier tube sensitivity. The gyrotron was, by far, the most reliable component of the experimental apparatus.

The limited time that was available for experimentation was used to study the angular symmetry of microwave injection on ECH efficiency, as determined from the soft X-ray spectrum, second harmonic emission, and the parametric wave interaction described previously. The temperatures deduced from the soft X-ray spectra (sensitive to electrons in the range 1-3 keV) were about 500 eV base plasma temperature, rising to about 820 eV during ECH (77 kW into torus) for injection at both $\pm 20^\circ$ from the normal to the toroidal current. The RF emission, for both waves of interest, showed distinct asymmetry. Injection at $+ 20^\circ$ (co-injection with respect to the current) produced larger signals than injection at -20°.

The temperatures from the soft X-rays are considerably higher than those we have measured previously with Thompson scattering under similar conditions. The difference is probably indicative of the different parts of the electron velocity distribution function to which each method is sensitive and not reflective of error in either measurement. (Similar differences were seen at JFT-2.) Presently, we do not understand the reasons for, or implications of, the asymmetry in the dependence of the RF emission on injection angle.

III. SUMMARY

Preliminary results of the ECH experiment using the MIT Versator II with polarized microwave radiation were obtained. Decreases in both loop voltage and line average plasma density were measured as a function of power and toroidal angle of microwave beam injection. Thompson scattering measurements indicate an increase in the central electron temperature from 226 eV to 350 eV for 60 keV of microwave power injected at a toroidal angle of 40°. Further experimental investigations of the dependence of ECH on the microwave injection angle and the linearity of its dependence on power were not conducted due to the breakdown of the Versator II tokamak. The angular symmetry of microwave injection on ECH efficiency and parametric wave interaction was investigated. These investigations showed a distinct asymmetry behavior for both polarizations.

APPENDIX A

ELECTRON-CYCLOTRON HEATING OF THE VERSATOR II TOKAMAK*

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Preliminary results of the electron-cyclotron heating experiment on Versator II using polarized microwaves are reported. Decreases in both loop voltage and line average density are measured as a function of power and toroidal angle of injection of the microwave beam. Thompson scattering measurements indicate an increase in the central electron temperature from 226 eV to 350 eV for 60 kW of microwave power injected at a toroidal angle of 40°. Other qualitative observations are discussed and a program of future work outlined.

I. INTRODUCTION

Heating of tokamak plasmas by microwaves at the electron-cyclotron resonance frequency is an attractive possibility, made practical by the recent development of the gyrotron as an efficient source of high-power millimeter radiation.[1,2,3] Previous experiments[4,5] have injected *unpolarized* microwave beams into a tokamak, observing significant heating ($\Delta T/T \cong 50\%$), with associated loop voltage and density decreases ($\Delta V_L/V_L \cong 35\%$, $\Delta\bar{n}_e/\bar{n}_e \cong 15\%$). Heating of the same proportion, with smaller loop voltage and density decreases, are observed in the present experiment.

In order to better understand the interaction of the microwaves with the plasma, an electron-cyclotron heating (ECH) experiment is being carried out on the Versator II tokamak (major radius R = 40.5 cm; minor radius a = 13 cm; plasma current Ip = 20 - 50 kA; ohmic heating power P_{OH} = 20 - 100 kW; line average electron density $\bar{n}_e$ = 0.5 - 1.5 x 10^{13} cm^{-3}; central electron temperature T_{e0} = 200 - 500 eV; discharge duration t = 20 - 40 ms) with a microwave beam that can be polarized for either the ordinary or the extraordinary mode and whose angle of injection relative to the toroidal magnetic field, can be varied over a

large range of angles. The microwave source used is the Naval Research Laboratory 35 GHz gyrotron (power $P = 20 - 150$ kW: pulse length $t \leq 20$ ms; output mode TE_{01} (circular)).

In Section 2 we describe the transmission system that converts the gyrotron output to the desired polarization and report in Section 3 our preliminary ECH results. The program for future work is outlined in Section 4.

2. MICROWAVE TRANSMISSION SYSTEM

To inject the microwave radiation into the tokamak from the high magnetic field side, required for extraordinary mode heating, the transmission system shown in Figure 1 is used. After propagating from the gyrotron in overmoded circular waveguide, the TE_{01} (circular) gyrotron output mode is converted to TE_{10} (rectangular) in a commercial mode converter. A gradual taper back to overmoded circular waveguide produces the TE_{11} (circular) mode, which is nearly linearly polarized for either the ordinary or extraordinary mode in the tokamak. The central region of the tokamak is illuminated by the plane mirror, supported in the limiter shadow from the waveguide. The toroidal angle of injection is 40°; the toroidal angle can be varied within ± 40° from perpendicular by rotating the last section of waveguide. This can be accomplished under vacuum conditions. The measured width of the microwave beam is 22° FWHM; power in the cross polarized electric field is down by 18 db; attenuation in the transmission system is about 1.5 db.

3. OBSERVATIONS AND MEASUREMENTS

The influence of the microwave pulses on the plasma was seen to depend strongly on its initial state. Without ECH, the discharge we discuss here was characterized by a nearly constant density, $\overline{n}_e \cong 1.2 \times 10^{13}$ cm^{-3}, lasting about 15 ms with $I_p \cong 33$ kA and loop voltage $V_L \cong 1.8$ V. The gyrotron was pulsed for 3 ms at the time of maximum current with the transmission system adjusted for the extraordinary mode. No increase in impurity line radiation was

observed. Heating the discharge from a different set of initial conditions will be discussed briefly later.

Two effects of the ECH pulse were immediately apparent. As seen in Figure 2, there was a decrease in the loop voltage and line average density during the gyrotron pulse. The loop voltage returned to its normal level after the pulse, while the density showed a marked increase compared to its value without an ECH pulse. The IN/OUT monitor showed that the plasma was well centered before the ECH pulse, moving toward the outside during the pulse only after the loop voltage and density had stabilized at their lowered values.

The dependence of $\Delta V_L/V_L$ and $\Delta\bar{n}_e/\bar{n}_e$ on microwave power, P_{ECH}, and injection angle, θ, is shown in Figures 3 and 4, respectively. Both effects are larger, and still increasing at high power, at the intermediate angles of 15° and 30°, while they are smaller, and show signs of saturation, at 0° and 40°.

Preliminary Thompson scattering measurements of the central electron temperature have been made for the case of $\theta = 40°$. T_{e0} rose from 226 ± 58 eV to 350 ± 89 eV for P_{ECH} = 62 kW, associated with an 11 percent decrease in V_L.

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Another set of initial conditions for a discharge we have studied were $\bar{n}_e \cong 6.6 \times 10^{12}$ cm^{-3}, I_p = 20 kA; V_L = 1.0 V at the time of the microwave pulse. Neither the current nor the density were constant for an extended period of time. Perpendicular injection of 60 kW of extraordinary mode radiation produced a 50 percent decrease in V_L and a 30 percent decrease in $\bar{n}_e$. The plasma moved toward the inside of the torus, with a substantial increase in the impurity line radiation. The loop voltage became very noisy after the pulse, with positive voltage spikes of 3-4 V, lasting a few hundred microseconds Thompson scattering showed T_{e0} to increase from 179 ± 21 eV to 275 ± 45 eV.

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The single-pass absorption coefficient for extraordinary mode heating should be increasing with angle, θ, throughout the range studied.[6,7] The observed decrease in loop voltage, an indication of heating, however, does not. It is necessary to understand the causes of the angular dependence so that the optimal injection angle for ECH can be found.

4. PROGRAM OF FUTURE WORK

The results reported here are preliminary; a more complete set of measurements is planned. We will be concerned with the dependence of ECH on the microwave injection angle and the linerarity of its dependence on power. The importance of interactions at the upper-hybrid layer will also be assessed.

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*Work supported by U.S. Dept. of Energy (Contract EX-77-A-34-1015).

•Also of JAYCOR, Inc., Alexandria, VA. 22304

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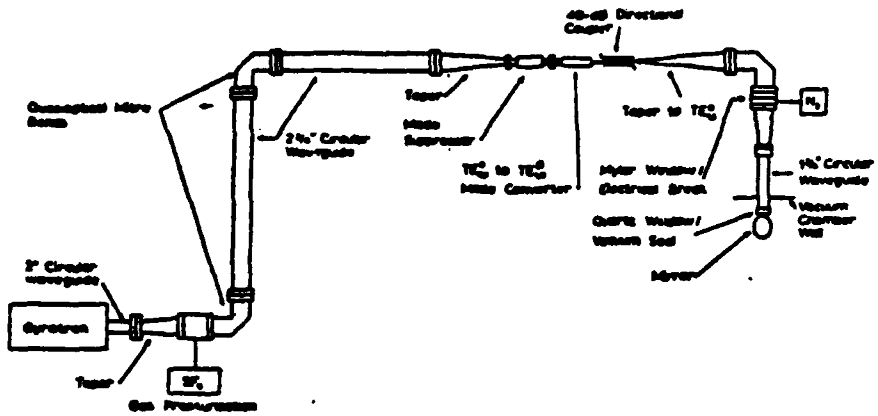
7.E. Ott, B. Hui, and K.R. Chu, Phys. Fluids 23, 1031 (1980).

VERSATOR ECH TRANSMISSION SYSTEM



VERSATOR ECH GEOMETRY

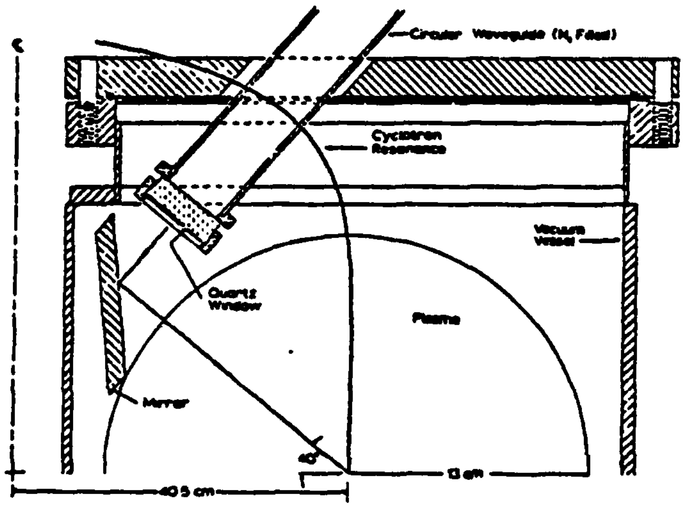


Fig. 1

Typical V_L & $\bar{n}_e$ During ECH

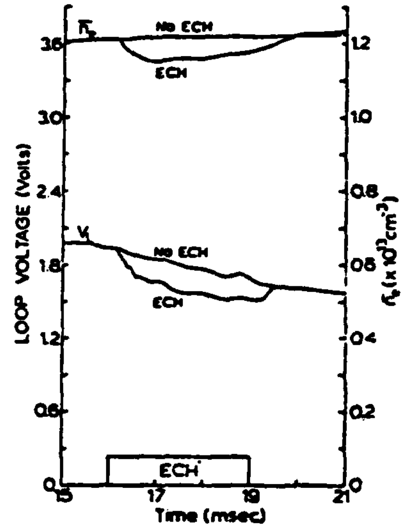


Fig. 2

Loop Voltage Decrease (P_{ECH}, $\theta_{injection}$)

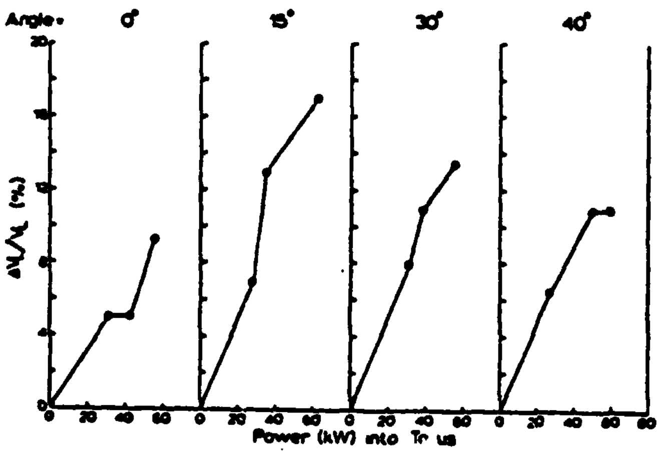


Fig. 3

Density Decrease (P_{ECH}, $\theta_{injection}$)

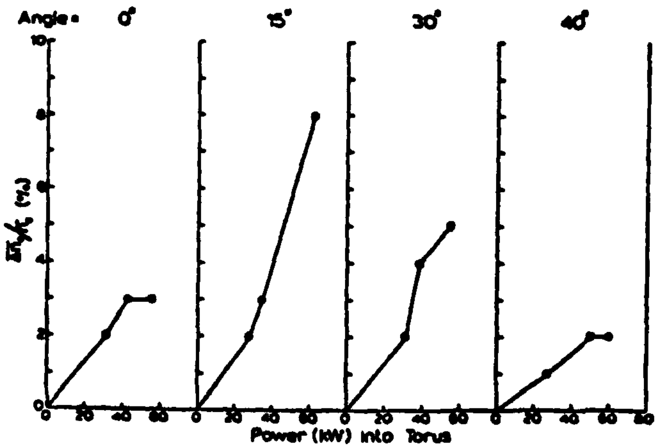


Fig. 4

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